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Obimon: An open-source device enabling group measurement of electrodermal activity

Krisztian Kasos[1,2] | **Szabolcs Zimonyi**[2] | **Bianka Gonye**[1,2] | **Ferenc Köteles**[3] | **Eniko Kasos**[1,2] | **Eszter Kotyuk**[2] | **Katalin Varga**[2] | **Andras Veres**[4] | **Anna Szekely**[2]

[1]Doctoral School of Psychology, ELTE Eötvös Loránd University, Budapest, Hungary

[2]MTA-ELTE Lendület Adaptation Research Group, Institute of Psychology, ELTE Eötvös Loránd University, Budapest, Hungary

[3]Institute of Health Promotion and Sport Sciences, ELTE Eötvös Loránd University, Budapest, Hungary

[4]Obimon Systems, Budapest, Hungary

Correspondence
Anna Szekely, Institute of Psychology, ELTE Eötvös Loránd University, Budapest, Hungary.
Email: szekely.anna@ppk.elte.hu

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Abstract

Electrodermal activity (EDA) provides the means to gauge the activity of the sympathetic nervous system. Assessment of EDA for research purposes requires measurement systems that are sensitive to small changes in arousal in the full measurement range, collecting, storing, and monitoring data. The objective behind designing a new open-source device was to be able to measure EDA simultaneously on many subjects, monitoring their activity in real time remotely and collecting high precision data suitable for analyses. To assure feasibility of simultaneous measurements on multiple subjects, the devices must be compact and wearable, without compromising data quality. Experiments were carried out using synchronized devices in group and single subject environments. Validity of EDA measurements of Obimon was demonstrated compared to a reference system (Nexus) during a breathing exercise, a short movie, and while exposed to loud computer-generated tones, using Pearson correlation, Passing-Bablok regression, and Bland-Altman analysis. Seamless management of several Obimons and real-time visualization of EDA via Android phone/tablet application from a large number of participants was demonstrated. Based on analyses of the data collected, we conclude that the Obimon device presented here is a valid and feasible tool for collecting EDA in single or multisubject environments.

KEYWORDS

arousal, electrodermal, group measurement, skin conductance, wireless

1 | INTRODUCTION

The measurement of electrodermal activity (EDA) has a long tradition starting in the 1800s, and it has been used in a wide variety of studies related to psychology. EDA is an efficient indicator of arousal reflecting the activity of the sympathetic branch of the autonomic nervous system (Boucsein, 2012). Practicality and ease of measurement have been cited as two of the reasons that made EDA a popular tool in research (Dawson, Schell, & Filion, 2007). Lie detection is one of the most prevalent areas where EDA has proved to be useful (Ben-Shakhar & Elaad, 2003), but elevated EDA levels may also reflect cognitive load on the information processing system (Walczyk, Igou, Dixon, & Tcholakian, 2013). EDA

measurements have also been used to differentiate between states of consciousness (Kasos, Kekecs, Kasos, Szekely, & Varga, 2018) and among electrodermal responses to stimuli conveying various emotions (Banks, Bellerose, Douglas, & Jones-Gotman, 2012; Kasos et al., 2018). Different characteristics of electrodermal activity are important indicators of emotional state and have been studied extensively in adults (Papousek & Schulter, 2001) as well as in infants (Ham & Tronick, 2008).

Handbooks of EDA specify tools for measurement and data processing extensively (e.g., Boucsein et al., 2012; Dawson et al., 2007). There are two basic measurement types: one with (exosomatic) and the other without (endosomatic) passing of a current between two points of the skin. Endosomatic recordings utilize the naturally occurring electrical properties of the skin to measure skin conductance. Eccrine sweat glands mostly under sympathetic control congregate in increased numbers at certain parts of the body. Sympathetic arousal and measured EDA have been closely tied to eccrine sweat gland innervation (Morrison, 2001; Nagai, Critchley, Featherstone, Trimble, & Dolan, 2004). Eccrine sweat glands also take part in thermoregulation; however, they respond with more sensitivity to psychologically significant stimuli than to thermal stimuli (Dawson et al., 2007). The palmar surfaces, the wrist area, the forehead, and the feet house eccrine sweat glands in proportionately higher numbers than other types of sweat glands, thus EDA measurements are usually reported from these body parts. Several measures are used as indicators of electrodermal activity: The tonic level of skin conductance (SCL) varies according to activity, ambient temperature, as well as individual characteristics. The phasic skin conductance response (SCR) reflects the response of the sympathetic nervous system to a certain stimulus. SCR attributes, such as amplitude and latency, provide important characteristics of the electrodermal response but also reflect individual differences of arousability traits (e.g., Crider, 2008). Electrodermal changes recorded in the absence of identifiable stimuli are called nonspecific responses; their amplitude, latency, and frequency may also characterize the individual or the situation (Dawson et al., 2007).

1.1 | Devices for measuring electrodermal activity

The spread and prevalence of wireless technology have inspired the field to develop ever smaller and smarter devices capable of operating without an external power supply and to record data for hours (in some instances, days) without interruption. Adams and colleagues (2017) provided an exhaustive review of existing solutions for EDA measurement. Most of the devices providing precision data sufficient for research purposes are high cost, which makes the simultaneous measurement of individuals in larger numbers financially demanding. Time synchronicity of measurement from multiple devices is another challenging problem. Finally, use of some available devices are restricted to certain parts of the body (e.g., Boyer et al., 2012; Carreiro et al., 2015; Garbarino, Lai, Bender, Picard, & Tognetti, 2014; Poh, Swenson, & Picard, 2010; Seoane et al., 2014). Existing tools used for EDA measurement are usually closed source, with a few exceptions. We argue that making the device open source has a significant benefit for at least two reasons. It provides an opportunity for researchers to tailor the software's profile for their specific needs while providing full transparency of the collected data—essential for research purposes.

1.2 | Validation of EDA systems

Validating devices and systems designed for electrodermal measurement is imperative. Savić and Geršak (2015) offer a solution for validating EDA systems from a purely technical specification point of view (e.g., resolution, precision, etc.). Although it is essential to ascertain that a device performs according to technical expectations, it is also important that its sensitivity to changes in arousal is comparable to other devices in the field.

Interestingly, comparisons or validations of different EDA measurement systems using data from human participants, instead of relying on electrical calibration testing, are rare in the literature. Schmidt and colleagues (2016) conducted a comparative study of a low-cost EDA measurement system with a commercial reference system (an MP150 GSR100C module from BIOPAC Systems). In this study, data from three subjects were used to evaluate EDA responses elicited by internal or external stimuli. Subjects were asked to produce a sound (the letter *A*) and to bite their tongue (these were considered as internal stimuli). Hand clapping by the experimenter was used as external stimuli. Measurements have been carried out consecutively, and not synchronously, due to authors' concern about possible sensing errors resulting from voltage interference.

Poh and colleagues (2010) validated a wearable sensor for long-term EDA assessment using synchronous measurements. They asked 26 participants to perform different types of tasks: physical ($N = 16$), cognitive ($N = 15$), and emotional ($N = 13$) while their EDA was measured from the index and middle finger on the right (reference system: Flexcomp Infinity) and the left (tested device) hands. Measurements from the distal forearm were collected as well. EDA from one participant was also measured continuously during daily activities for a week. Authors reported statistically significant Pearson's correlation coefficients between the filtered recordings from the two systems. Raw EDA signals were processed using a 1,024-point low-pass filter (Hamming window, cutoff frequency of 3 Hz) in MATLAB.

1.3 | Application for group assessment

Measuring EDA simultaneously in a group setting is sporadic in the literature; however, there are a few examples of group measurements going back almost 70 years (Asheim, 1951; Hagfors, 1970; Kaplan, 1963; Kaplan, Burch, Bloom, & Edelberg, 1963). Some existing EDA devices allow multiple measurements simultaneously; nonetheless, in a typical EDA measurement, a single person is monitored with a single device, even when data are later analyzed in groups (e.g., patients vs. controls). This setup allows a lot of room for externally induced "noise" (e.g., effect of loud noises, such as an ambulance passing by, different temperature and humidity on different days of measurement, etc.). When nonsimultaneously collected data are analyzed in a group design, these external artifacts cause unnecessary variability and may lead to false results. Furthermore, group assessment in real time is fundamental in some areas of research (e.g., developmental or social psychology).

Aggregating measurements from multiple subjects also requires accounting for unwanted effects of individual variability of both SCL and SCR. It is of vital importance for the device to measure with uniform sensitivity and noise across the full range of 1–100 μS. A low-level auditory stimulus, for example, may elicit skin conductance changes ranging from 0.1 to 10 μS (again, depending highly on individual arousability).

In this article, we introduce Obimon, a new, low-cost, small and open-source EDA device capable of synchronized measurements and monitoring of precision data from multiple devices. The applied system design assures uniform resolution and precision across the entire measurement range. We present data from three experiments to underlie reliability and feasibility of this EDA measurement system using individual or group settings in psychological research. In Experiments 1 and 2, we compared the Obimon to a reference system (Nexus) during synchronous measurements from individuals. Experiment 3 presents use of the Obimon system optimized for group setting.

2 | METHOD

2.1 | Participants

Participants were university students from several Hungarian universities, and their efforts were compensated via course credits. Participants were right-handed (based on self-report) in the first and second experiments. Exclusion criteria for the study included the use of psychiatric drugs, sedatives, and any psychiatric illness based on self-report. The study protocols were designed in accordance with guidelines of the Declaration of Helsinki and were approved by the Research Ethics Committee of the Faculty of Education and Psychology, Eötvös Loránd University. Three experiments were conducted independently, with different participants. Twenty subjects took part in the first experiment (N male = 4, N female = 16, mean age = 23.31, SD = 5.59), 14 were involved in the second experiment (N male = 3, N female = 11, mean age = 19.92, SD = 1.33), and 76 (N male = 14, N female = 62, mean age = 22.3, SD = 1.2) took part in the third experiment. One participant was excluded for malfunction of equipment from the first experiment.

2.2 | Design and procedure

The study consisted of three parts: first, we validated electrodermal measurements with the newly developed Obimon device, using Nexus as the reference system during a breathing exercise and a short movie in Experiment 1. Next, we compared measured response magnitudes by the tested device (Obimon) and the reference system (Nexus) to loud computer-generated tones (Experiment 2). Last, we applied the Obimon device for group measurement of a breathing exercise (Experiment 3).

All participants filled out an informed consent form, then electrodes were placed on their hands and devices were connected. They were asked to sit as still as possible during the experiments to avoid movement artifacts. Both Nexus and Obimon were synchronized to Internet time as was the computer that presented the stimuli for the participants. Time synchronization allowed us to locate specific events in the data.

In the first experiment, after time was synchronized, the experimenter started the 4-min breathing exercise audio recording and stayed in the room throughout the process, which was immediately followed by a short (approximately 5 min) movie. The reference device (Nexus) was connected to the electrodes on the left hand, and the tested device (Obimon) was connected to the electrodes on the right hand. Electrodes were placed on the medial phalanges of the left and right index and middle fingers.

In the second experiment, participants listened to 26 computer-generated sounds after the two exercises described in the first experiment. Placement of the reference system (Nexus) and Obimon was counterbalanced to rule out systematic differences in measurement that lateral differences may cause.

In the third experiment, we applied the Obimons for group measurement of a simple breathing exercise. Electrodes were attached to the medial phalanges of the middle and index fingers of the nondominant hand.

2.3 | Materials

A 4-min breathing exercise in Hungarian was used in all three experiments. Breathing instructions have been used

in electrodermal research to elicit responses since at least the 1960s (Blain, Mihailidis, & Chau, 2008; Edelberg & Burch, 1962; Hygge & Hugdahl, 1985; Rickles & Day, 1968; Rittweger, Lambertz, & Langhorst, 1997). The audio recording is available (Appendix S4 of the online supporting information). At the beginning of the recording (the first 35 s), participants were instructed to sit as still as possible, and an explanation was given of what was going to happen during the exercise. Starting from the 38th second, participants were asked to take a deep breath and hold their breath for five counts, which was said out loud on the recording. Next, they were instructed to slowly exhale. Starting from the 54th second, they were prompted again to take a deep breath, hold their breath, and slowly exhale. Afterward, participants were instructed to breathe normally, and further explanation was given of what would happen next: repeating the previous breathing exercise with eyes closed. At 1 min 40 s, participants were asked to close their eyes and keep them closed for the rest of the exercise, followed by a silent (30-s) block. At 2 min 20 s, instructions for the breathing section with eyes closed started, and the breathing exercise was repeated. Lastly, at 3 min 22 s, participants were instructed to sit still with eyes closed for another 30 s. In the first and second experiment, besides the breathing exercise participants watched an approximate 5-min movie (Appendix S5 of supporting information). The movie describes a cartoon character playing chess with his imaginary alter ego. Watching the movie may evoke emotions of happiness, at times compassion, and possibly sadness. At the 27th second of the movie, human hands slap down a chessboard on a wooden table. We chose to analyze responses to this event, considered as a psychologically significant stimulus.

In the second experiment, we employed a common psychological paradigm to examine autonomic reactivity to loud tones, eliciting subjects to orientate to changes in the environment (see, e.g., Mueller-Pfeiffer et al., 2014). Twenty-six 1000 Hertz computer-generated loud beeping sounds were played. Interstimulus intervals were randomized between 27 and 52 s. The sounds were played at 90 dB from JVC HA-RX900 headphones. Participants' responses were measured in a single subject environment with an experimenter always present.

Skintact FS-RG1 disposable (32×41 mm) Ag/AgCl electrodes (Leonhard Lang GmbH, Innsbruck, Austria) were used for the measurement of electrodermal activity with an electroconductive gel that was used to establish contact between the electrode and the skin (Posada-Quintero et al., 2017).

2.4 | System design of the tested device and measurement details

Figure 1 represents the overall system architecture of the new EDA device (see obimon.com). Recent advancements in high precision analog front-end design allow compact yet more precise measurements of small signals such as skin conductance.

Many commercial EDA devices perform complex analog signal preconditioning in order to amplify and convert the signal suitable for input to an analog-to-digital converter. In contrast, the Obimon utilizes a 22-bit resolution A/D converter with very low noise specification (MCP3551/3) eliminating the need for complex preamplification or filtering, nor is it needed to subtract an estimated SCL value before analog-to-digital conversion, further improving the precision of measurements. For comparison, several small footprint EDA devices use 10- or 12-bit resolution (e.g., Affanni & Chiorboli, 2015; Boquete et al., 2012; Kappeler-Setz, Gravenhorst, Schumm, Arnrich, & Tröster, 2013; Poh et al., 2010; Savić & Geršak, 2015; Schmidt et al., 2016). The difference in resolution is from 100 to 1,000 times.

Another important design choice made was the use of a so-called zero-drift operational amplifier (MCP6V31) on the

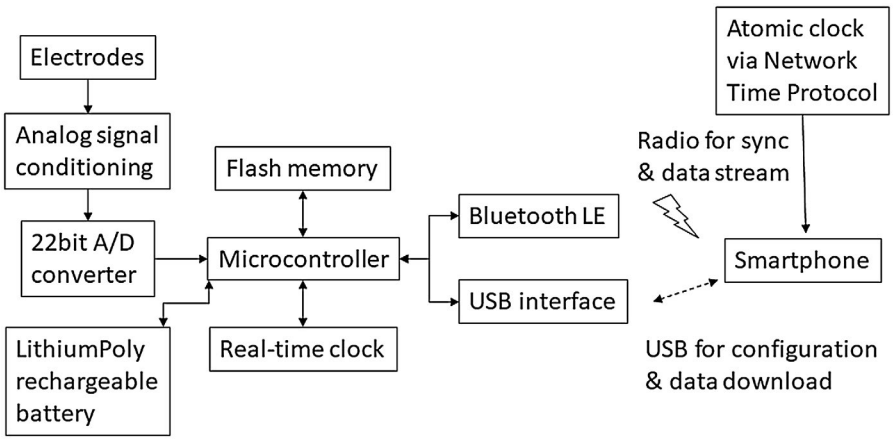

FIGURE 1 Functional system block diagram

input signal, which has significantly lower offset errors and noise at low frequencies than traditional instrumentation amplifier-based EDA designs.

The third significant design choice was due to the requirement of having uniform precision across the entire measurement range. Some existing EDA devices measure the resistance (MOhm) actually and then calculate the inverse in software to get the desired conductance value in units of μS. As a result, these devices tend to have much lower resolution at high EDA ranges. This means that subjects having high SCL value (e.g., > 10 μS) will have significantly lower measurement quality than subjects having low SCL (e.g., < 3 μS). Additionally, small EDA signals may completely disappear or may be masked by noise. To eliminate this problem, in the case of the Obimon, we applied a constant voltage (0.4 volts) EDA method where the sensed current across the body is passed into the aforementioned zero-drift amplifier in a transimpedance configuration. In other words, the sensed current is directly converted into voltage and then to digital value through the AD converter. A significant benefit of this design is that, since the sensed current is proportional to conductance, the device has constant resolution and precision across the entire measurement range regardless of the subject's base SCL value.

The contacts of the electrodes are placed directly on the enclosure of the device itself, so that the leads can be of minimal length, reducing the noise on the very low-level electrical signals. Placement of the Obimon device is possible on most body parts; however, fingers or palms of children and adults and the feet of babies are the most comfortable places for measurements (see Figure 2).

Numerous sources (e.g., Braithwaite, Watson, Jones, & Rowe, 2013) suggest a high oversampling rate of 100 or even 1,000 samples per second and postfiltering in software. In Obimon, this step is delegated to the device itself, as the necessary oversampling and filtering is done before the converted digital data are stored (approximately 30,000 samples per second oversampling). The resulting sample rate has been chosen to be eight low-noise, high precision measurement samples per second and is directly applicable to EDA measurements without further smoothing and/or filtering. The sampling rate could be changed up to 60 samples per second if needed.

Time synchronization is an important requirement when performing measurements on multiple devices. Obimon supports two ways of time synchronization. In both cases, the time synchronization is obtained with the help of the publicly available Obimon app run on a smartphone or tablet. The smartphone application, when running as a service, synchronizes itself to a precision global clock using Internet Network Time Protocol (NTP). It is possible to synchronize each Obimon manually by connecting it to a smartphone by a USB cable. When connected, Obimon automatically synchronizes to the NTP time within less than a second (used in Experiment 1 and 2 in the present study). Alternatively, synchronization can be broadcast wirelessly every second to all Obimon devices nearby from a designated Obimon device set to "transmit mode." Obimon devices set to "listen to transmission of time synchrony" receive such broadcast signals prior to measurements and adjust their clocks (used in Experiment 3 in the present study). The first manual method is applicable for small-scale experiments of one or only a few devices, whereas the second method is more appropriate when there are many devices in an experiment, and one can be designated to broadcast only "perfect" time synchrony. Once synchronized, Obimons use their own crystal-driven clocks to time stamp every sample.

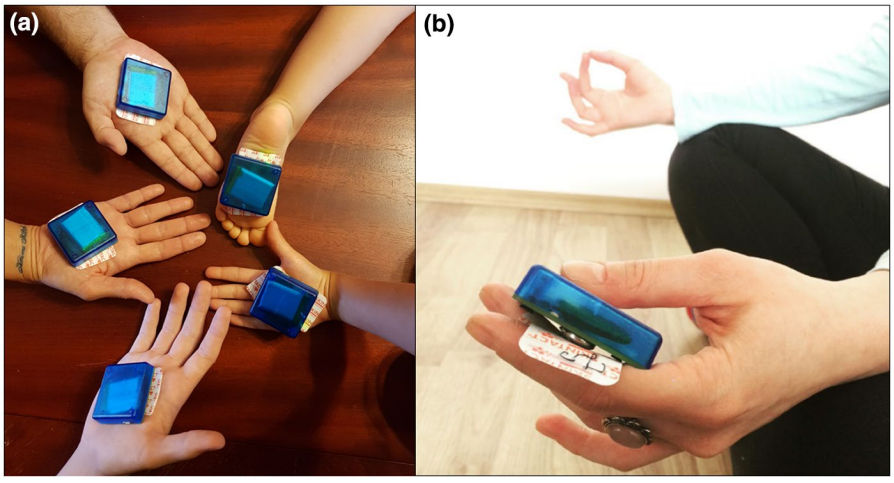

FIGURE 2 Most comfortable placement of the Obimon is on the palm or on the foot, but measurement on the finger is also convenient. (a) Upper left, clockwise: Device is placed on the palmar surface of the right hand of a 45-year-old male, left foot of a 4-year-old girl, and right hand of a 6-year-old girl, a 16-year-old male, and a 47-year-old female. (b) Direct contact of the electrodes with the device placed on the medial phalanges of the left index and middle fingers of a young female, while meditating

The EDA samples with their time stamp are stored on a nonvolatile FLASH memory chip inside the Obimon device. This on-board memory is capable of storing up to 2 million samples or approximately 72 hr of data. Since every sample has a coordinated universal time attached, it is very easy to identify exact measurement sessions and synchronize data from numerous devices later. Samples are also transmitted wirelessly using Bluetooth Low Energy (BLE) technology. BLE has the advantage that all recent smartphones support this technology, so there is no need for an extra receiver device. Also, BLE supports very low power operation, so the integrated battery can supply the device for 24–36 hr while measuring and more than 30 days while idle.

Since the recorded data can grow very large, we chose to use USB as the means to download the contents of the memory to an Android phone. The format of data is TSV (tab separated value) and can be stored or emailed from the Android application.

It is often necessary to monitor the measurements in real time. An important feature of the Obimon Android application is that it can listen to all Obimon devices broadcasting measurements in the vicinity of the smartphone or tablet. In practice, the receiving range is around 100 m. There is a limitation of the total channel capacity of BLE, however, so the transmit frequency needs to be adjusted if the number of active devices is very high in close proximity. The application allows adjustment of the transmit rate, so that the radio channel is kept under saturation. Screen size may also limit the number of devices that can be meaningfully tracked at the same time. It is important to note that the storage on the device stores all data, regardless of the transmit frequency setting.

2.5 | The reference system

The NeXus-10 MKII device and the BioTrace+ (v 2015) software (Mind Media BV, Herten, the Netherlands) were used as the reference system. It is a reliable and extensively utilized system in psychophysiological research (Bogdány, Boros, Szemerszky, & Köteles, 2016; Dömötör, Doering, & Köteles, 2016; Köteles, Dömötör, Berkes, & Szemerszky, 2015; Szemerszky, Dömötör, Berkes, & Köteles, 2016). Skin conductance data were recorded with a sample rate of 32/s and down-sampled to the recording rate of the Obimon system in the first experiment, while left at 32/s rate in the second experiment.

2.6 | Data analyses

Raw data were inspected for artifacts and to determine that the exclusion criteria fulfilled the guidelines provided by Kocielnik and colleagues (Kocielnik, Sidorova, Maggi, Ouwerkerk, & Westerink, 2013). More than a 20% second-to-second rise and more than a 10% second-to-second drop in baseline SCL was deemed as an artifact. Typical skin conductance values measured from the palmar surfaces range between 2 and 20 μS (Dawson et al., 2007); however, there is great individual variability. Therefore, a minimum of 0.05 μS and a maximum of 60 μS for SCL filter were also applied, as recommended by Kleckner and colleagues (2017). Raw data were used to compare Obimon to Nexus (Experiment 1, breathing instructions) and to present group measurement (Experiment 3). To demonstrate the capacity of Obimon to detect responses to psychologically significant stimuli, we chose a scene from the beginning of the short film in the 27th second when human hands suddenly banged down a chessboard on a wooden table (Experiment 1). Moreover, we exposed participants to 26 loud computer-generated short tones (Experiment 2). For analyzing SC responses, we used Ledalab 3.4.9 (Benedek & Kaernbach, 2010). Gaussian smoothing was applied to raw data to decrease error noise. SCR and SCL were separated by optimized continuous decomposition analysis (Benedek & Kaernbach, 2010). We set a 4-s window 1 s after stimulus onset for analyzing SCRs. The minimum threshold for SCR responses was set to 0.01 μS.

2.7 | Statistical analyses

We employed three methods to test the validity of the measurements taken by Obimon. Based on the practice of other studies to validate EDA devices (e.g., Poh et al., 2010), Pearson correlation was used to test the degree of association between the tested and the reference device. We used Passing-Bablok regression as one of the recommended analyses for method comparisons (Passing & Bablok, 1983). The Passing-Bablok regression is based on the following premise: if two measurement methods are equal, then we can express this with the following formula $Y = X$. This formula can also be expressed in terms of a regression equation $Y = 1X + 0$, where 1 is the slope and 0 is the intercept. However, we accept some measurement error so we calculate the 95% confidence interval for the slope and also for the intercept. After regressing Y on X, the Passing-Bablok regression yields a regression equation and also calculates the 95% confidence interval for the slope and for the intercept. If the calculated confidence interval for the constant (intercept) includes 0 and the calculated confidence interval for the slope includes 1, we may conclude that the two methods are equivalent.

To complement the correlation and regression analysis, Bland-Altman (Bland & Altman, 1986,1999) analysis was conducted to examine whether there is a trend in measurement differences between Obimon and Nexus. Bland-Altman analyses have been used extensively in the medical field to validate devices designed to measure various physiological phenomena, cited in over 11,500 publications (Myles & Cui, 2007). It has been used to validate devices measuring cardiac output and EEG devices (e.g., Bogdány et al., 2016; Niedhart et al., 2006; Opdam, Wan, & Bellomo, 2007). The method

proposed by Bland and Altman is a graphic method to assess the agreement between values measured by a reference and tested device, and it is based on the premise that we do not know which device measures the true value of a property. As a compromise, Bland and Altman suggest using the average of the reference and tested values (x axis) plotted against the difference (reference value-tested value) between measurements taken by the reference and tested devices. The Bland-Altman plot allows for easy visualization of the agreement of our data by constructing the average difference and the upper and lower limit of agreement, which is 1.96 *SD* away from the solid line. If there was a perfect agreement between devices, all observations would fall on the solid line and the average difference between devices would be 0—in this case, the devices would measure exactly the same value. However, we expect some deviation from the solid line, but as long as observed values remain 95% of the time in between the dashed lines, we may conclude that the tested device measures in agreement with the reference device. Bland-Altman analysis assumes a normal distribution of the differences, thus a test of normality is suggested. In case the differences are not normally distributed, a logarithmic transformation of the data is recommended. To test any systematic differences between the values measured by the reference and tested device, a one sample t test is performed to see if the average difference is significantly different from 0. If the t test is significant, we can conclude that the tested device consistently measures either a lower or a higher value than the reference device. The third step is to test whether there is a significant relationship between the average values of the two devices and the differences. If there is a significant correlation, then there is a systematic trend in differences. If there was a significant correlation, then, for example, those who have low skin conductance would measure close to the average (solid line); however, those who have higher skin conductance would measure further from the average (solid line). Since we do not measure from the same body part, differences in skin conductance values are expected. With the use of Bland-Altman analysis, we are more interested in whether there is a visible trend in the distribution of differences. In a Bland-Altman plot, differences should be randomly distributed with no significant correlation between measurement differences and average measurement.

3 | RESULTS

3.1 | Results of Experiment 1: Breathing exercise

3.1.1 | Validating Obimon during a breathing exercise and a short movie

Average within-subject correlation of EDA measurement by Obimon on subjects' right hand and EDA measurement by the reference (Nexus) on their left hand was used to assess validity of the tested device. First, we calculated a correlation value for each subject using SCL values measured at the left and the right fingers at 1,921 time points (8/s) during the breathing exercise. Then, we averaged these 19 within-subject correlation values.

The average within-subject correlation between the reference (Nexus) and tested (Obimon) measurements during the breathing exercise of all 19 participants of Experiment 1 resulted in an average within-subject Pearson $r = 0.92$. Correlation values of the participants ranged between 0.43 and 0.99. Correlation for a randomly chosen participant (Number 13) was $r(1919) = 0.99$, $p < 0.001$ (Figure 3a). Distribution of within-subject correlations is depicted in Figure 3b. Raw data, correlations, and figures for all participants are provided in Appendix S1 of the supporting information.

Passing-Bablok regression was conducted using a single pair of data points for every participant (the average skin conductance for the 4 min of the breathing exercise) to assess whether the measurements taken by Obimon and Nexus differ significantly (Figure 4a). The assumption of linearity was not violated according to the CUSUM test of linearity with a p value of 0.336. According to the Passing-Bablok regression, the slope's confidence intervals include 1, slope = 1.101 (95% CI 0.898–1.295). The intercept's confidence intervals include 0, intercept = −0.359 (95% CI −1.252–0.793). According to our results, the values measured by the two devises are not significantly different.

To assess if there is a systematic trend in differences, we conducted Bland-Altman analysis using the average skin conductance for the 4-min interval of the experiment (Figure 4b). The Bland-Altman plot shows that only one participant's test device (Obimon) score deviated more than 1.96 standard deviations from the average difference. The one sample t test testing the hypothesis that the average difference (mean = −0.22, $SD = 0.88$) is significantly different from 0 produced a nonsignificant result $t = -1.12$, $p = 0.278$. The Pearson correlation between the average of Nexus and Obimon and the differences between Nexus and Obimon resulted in $r(17) = -0.30$, $p = 0.173$. These results show that the Obimon measures are in agreement with the reference system Nexus. The average difference between the two devices is not significantly different from zero, and importantly there is no systematic trend in measurement differences (differences are randomly distributed in the plot).

3.1.2 | Results of the SCR analysis of psychologically significant stimuli from a short movie

To test sensitivity of the devices to electrodermal responses to psychologically significant stimuli in a real-life situation (e.g.,

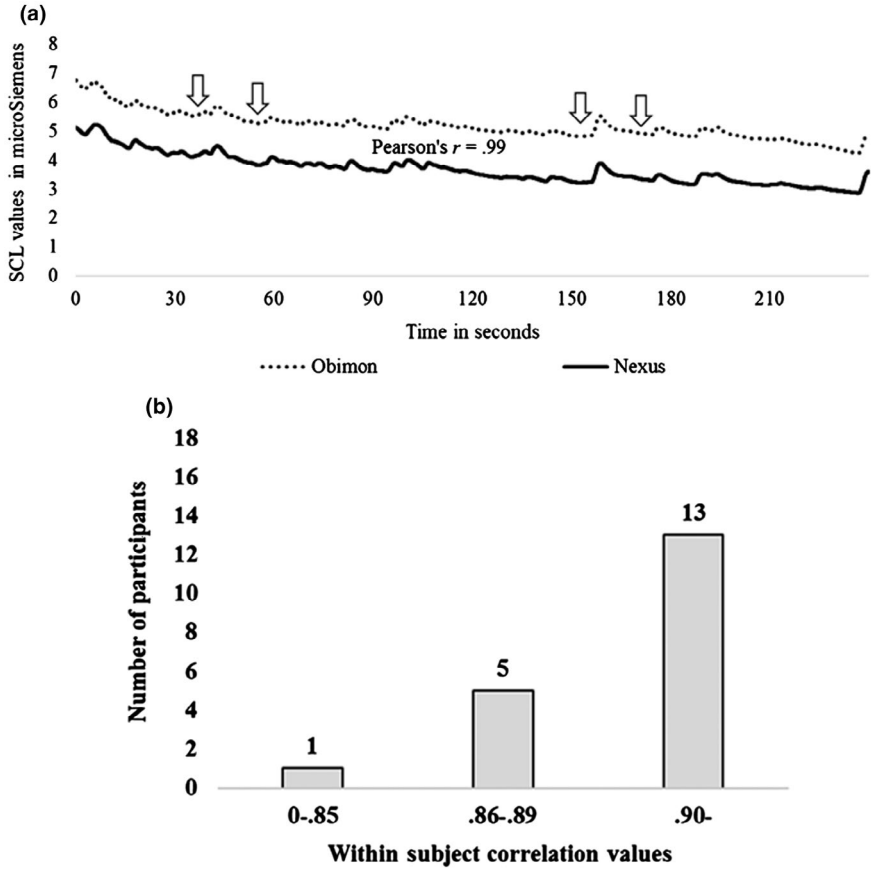

FIGURE 3 (a) Breathing exercise measured by the reference (Nexus) device on the nondominant hand and the tested (Obimon) system on the dominant hand for Participant 13. Arrows represent the "breathe in" instruction of the breathing exercise at 38, 54, 151, 172 s. (b) Distribution of within-subject correlations

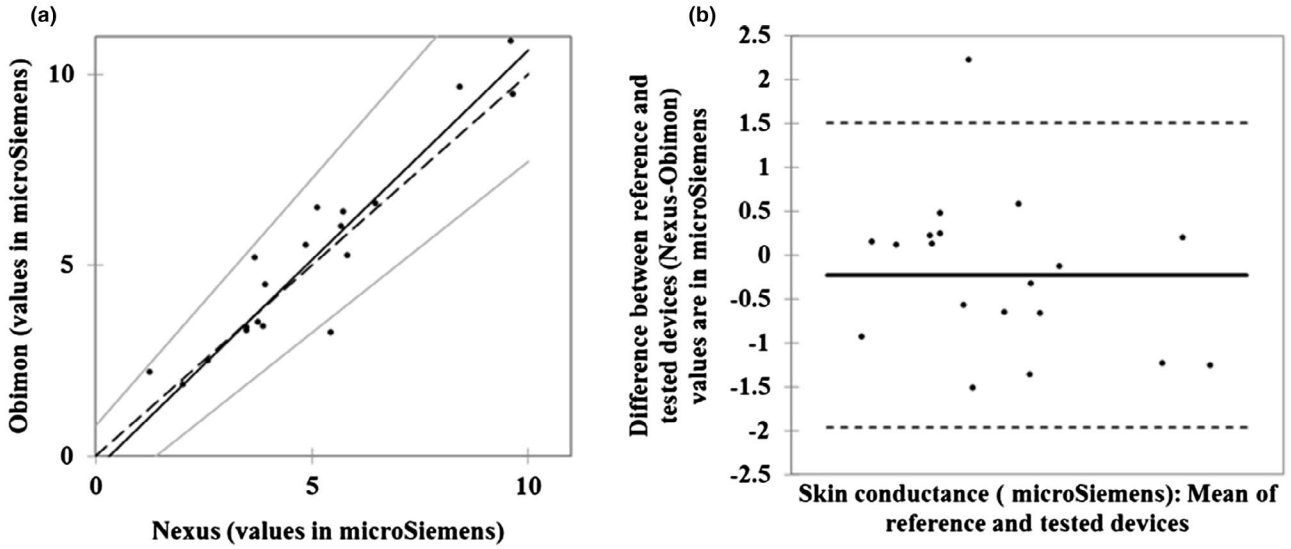

FIGURE 4 (a) The 4 min of the breathing exercise for all participants. Passing-Bablok regression of Obimon and Nexus. Dashed line represents the regression line if the intercept is 0 and the slope is 1. Solid black line represents the actual regression line. Gray lines represent the 95% CIs. (b) Bland-Altman plot of skin conductance level measured by the reference system (Nexus 10) and tested device (Obimon). Solid line represents the mean difference between the reference and tested device, dashed lines represent the ± 1.96 *SD* threshold for the whole sample

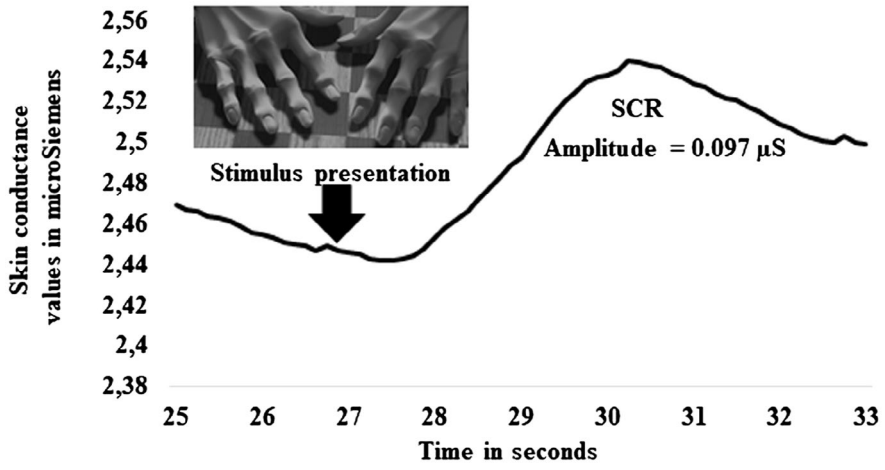

FIGURE 5 Participant 8 was selected randomly to demonstrate a typical SCR detected by Obimon at the 27th second of the movie, when human hands slap down a chessboard on a wooden table

while watching a movie), we selected a scene from the movie that participants watched in Experiment 1 (Figure 5). We analyzed data only when responses were detected on both hands (from the reference device: Nexus connected to the left hand, from the tested device: Obimon connected to the right hand). Of the 19 participants, six showed no electrodermal responses to this stimulus, and in two cases responses were detected only by Obimon. This left 11 participants with valid bilateral responses.

Pearson correlation of the SCR amplitudes was conducted to assess the relationship between the measurements of Obimon and Nexus. The analysis yielded a significant between-subjects correlation, $r(9) = 0.93$, $p < 0.001$. According to the Passing-Bablok regression (Figure 6a), the slope's confidence intervals include 1, slope = 1.334 (95% CI 0.941–2.147). The intercept's confidence intervals include 0, intercept = −0.014 (95% CI −0.529–0.090). The assumption of linearity was not violated according to the CUSUM test with a $p = 1.00$. This analysis shows that the SCR values measured by the two devices do not differ significantly. The Bland-Altman analysis (Figure 6b) shows that the measurement differences between the two devices are close to 0 and the Pearson correlation between average SCR detected (x axis) and bias (y axis) did not reach significance, thus differences are randomly distributed without displaying a systematic trend.

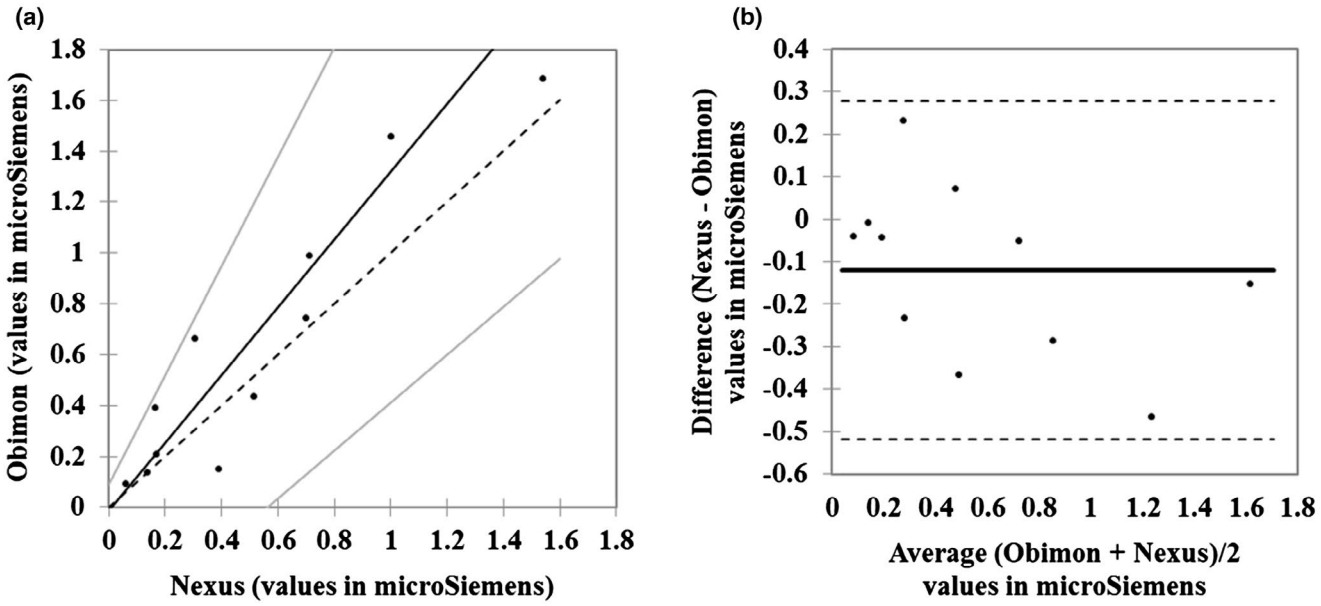

FIGURE 6 (a) Skin conductance responses to psychologically significant stimulus. Passing-Bablok regression of Obimon and Nexus. Dashed line represents the regression line if the intercept is 0 and the slope is 1. Solid black line represents the actual regression line. Gray lines represent the 95% CIs. (b) Skin conductance responses to psychologically significant stimulus. Bland-Altman plot of SCR to psychologically significant stimulus measured by the reference system (Nexus 10) and tested device (Obimon). Solid line represents the mean difference between the reference and tested device, dashed lines represent the ± 1.96 *SD* threshold for the whole sample

3.2 | Results of Experiment 2: SCRs to loud tones

We obtained SCR data from the two devices after presenting subjects with 26 loud tones (intended to elicit orientation to environmental changes) to validate measures of peripheral reactivity. Out of the possible 364 responses (14 participants × 26 tones), Obimon detected 357 responses (98.0%) and Nexus detected 358 responses (98.3%). For the analysis of SCRs, we used Ledalab 3.4.9 (Benedek & Kaernbach, 2010). SCR amplitudes were extracted by optimized continuous decomposition analysis, where response amplitude corresponds to the sum of SCR amplitudes (which are reconvolved from phasic driver peaks) in the determined response window (Benedek & Kaernbach, 2010). Average response magnitude was calculated for all 14 participants by using all 26 response amplitudes (including 0 responses) and averaging them (Dawson et al., 2007; Payne, Schell, & Dawson, 2016). Between-subjects Pearson correlation between average response magnitudes detected by Obimon and Nexus devices resulted in $r(12) = 0.862$, $p < 0.001$. Within-subject correlations were calculated for all participants based on the 26 SCR amplitudes obtained from the two devices (Table 1). Within-subject correlation between Obimon and Nexus was $r = 0.75$ on average, indicating that responses measured by the two devices are alike.

Passing-Bablok regression was conducted (Figure 7a) to evaluate the agreement between the devices. The slope's confidence intervals include 1, slope = 1.160 (95% CI 0.724–1.837). The intercept's confidence intervals include 0, intercept = −0.012 (95% CI −1.104–0.457). According to the CUSUM test, the assumption of linearity was not violated, $p = 0.938$. The SCR values measured by the two devices do not differ significantly. Bland-Altman analysis (Figure 7b) shows that the measurement difference between the two devices does not differ significantly from 0, $t(13) = -0.76$, $p = 0.46$. The Pearson correlation between average SCR magnitude detected (x axis) and bias (y axis) did not yield significant results; according to our analysis, there is no systematic trend in the distribution of the differences.

3.2.1 | Differences contributed to age and gender

To rule out systematic bias in connection to age in the first and second experiment, Pearson correlation was conducted between age and measurement differences between devices. The results for the Pearson correlation between SCL differences measured by the two devices and age (Experiment 1) are as follows: $r(17) = 0.10$, $p = 0.676$. The results of the Pearson correlation between differences in SCR magnitude and age (Experiment 2) are as follows: $r(12) = 0.16$, $p = 0.572$.

To rule out systematic bias in connection to gender, independent samples t test was conducted with the dependent variable SCL differences measured by the two devices (first experiment) and the independent variable gender $t(17) = 0.72$, $p = 0.542$. Independent samples t test was conducted with the dependent variable SCR magnitude differences (second experiment) and the independent variable gender $t(12) = -0.39$, $p = 0.701$.

Based on our results, neither gender nor age contributes to differences in measurement.

TABLE 1 Average response magnitudes (in microSiemens) for Obimon and Nexus (after presentation of loud, computer-generated tones) and within-subject Pearson correlations

Participant	Obimon response magnitudes	Nexus response magnitudes	Within-subject correlations (Pearson's r)
1	0.71	1.08	0.91
2	0.62	0.55	0.93
3	2.95	2.38	0.94
4	1.87	1.14	0.97
5	1.21	1.04	0.80
6	1.81	2.17	0.80
7	2.78	2.02	0.47
8	2.14	2.32	0.85
9	1.51	2.40	0.56
10	1.30	1.59	−0.40
11	1.28	0.91	0.80
12	0.64	0.55	0.96
13	3.08	2.68	0.92
14	1.23	0.94	0.94

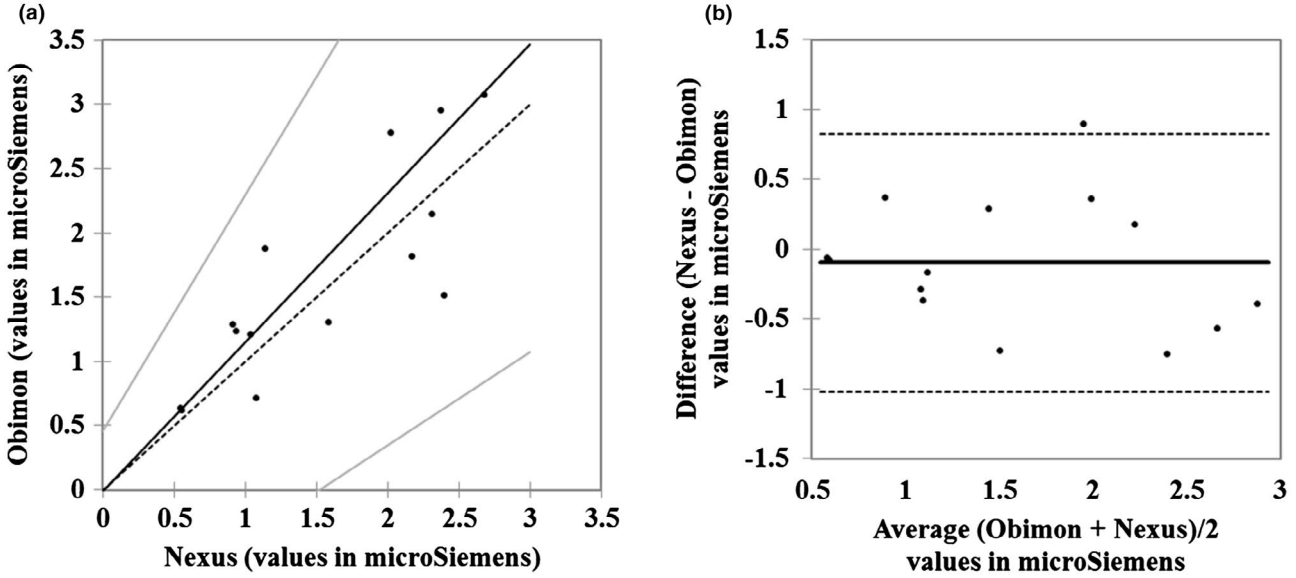

FIGURE 7 (a) SCR magnitudes to computer-generated tones. Passing-Bablok regression of Obimon and Nexus. Dashed line represents the regression line if the intercept is 0 and the slope is 1. Solid black line represents the actual regression line. Gray lines represent the 95% CIs. (b) Bland-Altman plot of SCR magnitudes measured by reference system (Nexus 10) and tested device (Obimon). Solid line represents the mean difference between the reference and tested devices, dashed lines represent the ± 1.96 *SD* threshold for the whole sample

3.3 | Results of Experiment 3: Group application

With the participation of 76 students, we measured skin conductance during the breathing exercise, as previously described. The electrodes were placed on the nondominant hand, and the participants were instructed to sit as still as possible during the exercise. When averaging all participants' electrodermal activity, responses to the breathing instructions become clearly visible (Figure 8). The SCL of participants (see Appendix S3) show high variability, which is well portrayed by the area between the lower and the upper bound lines representing +1 and −1 standard deviation away from the average. It is noteworthy that the response to the first breathe in instruction at 38 s is the strongest response translating into higher amplitudes. The second response 14 s later is smaller in amplitude. During the third and fourth instructions, participants had their eyes closed, responses are smaller than the first two responses, but they show a similar pattern.

4 | DISCUSSION

In this article, we introduce a new device designed to measure electrodermal activity in psychological experiments. The Obimon opens new avenues in EDA research and therapy since this compact and wearable device not

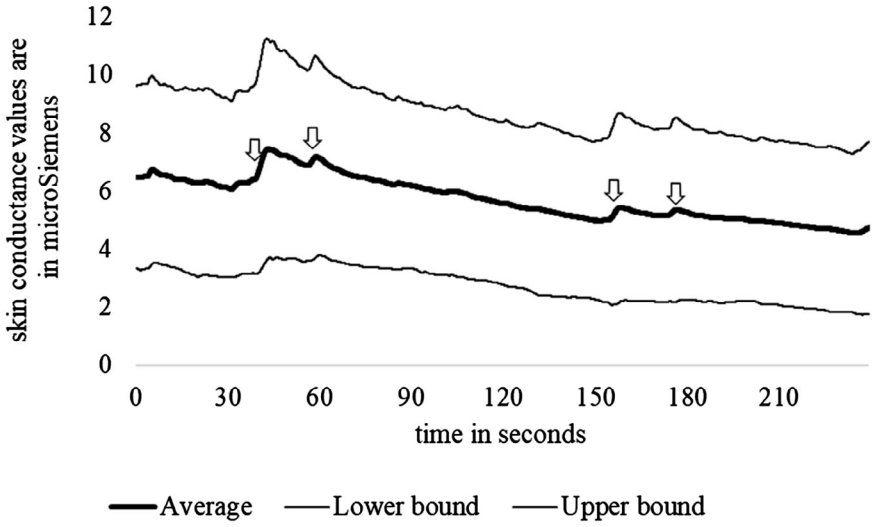

FIGURE 8 Average skin conductance level during the breathing exercise. Average = average skin conductance during the measurement; lower bound = average minus one standard deviation at every time point; upper bound = average plus one standard deviation at every time point. Arrows represent the "breathe in" instruction of the breathing exercise at 38, 54, 151, 172 s

only allows for the collection of high precision data but also enables simultaneous measurement from a large number of subjects. It is possible to use a designated Obimon device for time synchronization of all other devices in a group. This feature is unique in the field. Obimon's wireless technology allows the effective and seamless recording and display of EDA data in a group setting. EDA read from multiple devices can be displayed simultaneously in a real-time line chart. Monitoring measurements remotely in real time could serve as biofeedback for individual use, it could provide important additional information for therapeutic or research purposes, and it could also be utilized in practical fields of EDA, such as lie detection. The absence of cables also reduces the possible number of malfunctions and reduces measurement noise. The Obimon is open source, allowing researchers to tailor the software's profile to their specific needs.

To evaluate this new device, we carried out simultaneous measurements with Obimon and the reference system, which allowed for a direct comparison between the two systems. For stimuli, we used a short breathing exercise, a scene from a short movie, and in a separate experiment 26 computer-generated tones, mimicking the EDA level changes and electrodermal responses typical in psychological experiments.

In Experiment 1, we demonstrated that measurements taken with the Obimon have high correlation (during the breathing exercise and when measuring responses to psychologically significant stimuli) with the reference system (Nexus). Based on the results of the Passing-Bablok regression, the measured SCL and SCR values do not differ significantly. The Bland-Altman analysis revealed that the electrodermal activity measured by Obimon and Nexus is without significant bias. Although our analysis did not reveal significant differences between the two devices, we cannot completely rule out that device differences were masked by differences caused by laterality since we placed Obimon always on the right hand and Nexus on the left hand (lack of counterbalancing in this experiment is an obvious limitation). We also attribute the high but not perfect correlations to the fact that we measured from opposite sides of the body. Differences between the two sides of the body have been reported (Banks et al., 2012; Kasos et al., 2018; Picard, Fedor, & Ayzenberg, 2016). Great individual differences in electrodermal activity of different body parts have also been reported in the literature. For example, Payne and colleagues (2016) reported a strong average within-subject skin conductance correlation between the left finger and left toe ($r = 0.66$). However, the range of correlation for individuals ranged between $r = 0.31$ and $r = 0.99$. This wide range could result from different density of sweat gland distributions or different thickness of the skin. Although simultaneous measurements are desirable when it comes to validation of newly developed devices, the tested and reference devices cannot occupy the same anatomical location. When validating a device, setting acceptable differences prior to the measurement would be advantageous. However, this is practically impossible because of great individual differences in responding at different body parts. Thus, measurement differences cannot be completely separated from those coming from laterality, body parts, or differences in values measured by the two devices. Counterbalancing measurement locations can minimize laterality effects. This is a critical point that we recommend employing when comparing devices in simultaneous measurements. Therefore, in Experiment 2, we counterbalanced measurement locations. Our results showed high between- and within-subject correlation between average response magnitude measured by the two devices. Further, Bland-Altman analysis and Passing-Bablok regression did not reveal significant differences between measured average response magnitude. Counterbalancing minimized the chance that lateral differences masked differences in electrodermal activity measured by the two devices. Thus, we can be more confident that measurements by the two devices did not significantly differ.

Obimon opens new perspectives regarding real-time group measurement of electrodermal activity. Our results from Experiment 3 demonstrate that a large number of participants (limited only by the devices at hand) can be measured simultaneously, with a high degree of temporal precision. Measuring EDA in a group-design could reduce noise created by environmental differences and, thus, enhance precision necessary in this line of research. Our results show great individual variability in electrodermal activity. Most participants displayed EDA levels around 6 μS, but 68% of the participants displayed levels anywhere between 2 and 12 μS. Our results are lower than relevant results, which reported 12.36 μS average skin conductance for their participants (Payne et al., 2016).

According to previous findings, EDA measurements could be sensitive indicators of individual differences (e.g., Naveteur & Freixa i Baque, 1987; Yoshino, Kimura, Yoshida, Takahashi, & Nomura, 2005) and pathological characteristics (e.g., Baker et al., 2017; Kochanska, Brock, Chen, Aksan, & Anderson, 2015; Thorell, 2009). Obimon in a group setting could be appropriate to assess large numbers of individuals simultaneously to identify individual characteristics using the same stimuli in the same environment. Measuring covert responses of large groups could also prove valuable in research concerning group behavior and group dynamics. Moreover, measurements outside of the laboratory call for devices that are easy to use, can be attached to alternate measurement spots, are wireless, and allow online monitoring.

One of the limitations of the present study is the narrow age range of the participants and the unbalanced gender

distribution in our sample. The other limitation is that we did not measure from the palms, a common place from which to measure electrodermal activity.

In summary, in the present article we introduced and successfully validated the Obimon device, which is suitable for measuring electrodermal activity with appropriate precision necessary in research. System characteristics of the Obimon device and its open source software allowing group assessment and real-time display were portrayed. Along with the obvious advantages mentioned above, the ease of use of the device to collect high precision data makes it suitable for individual, clinical, and research purposes.

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ORCID

Ferenc Köteles https://orcid.org/0000-0001-5460-5759
Anna Szekely https://orcid.org/0000-0002-7590-7681

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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